Attractor Solution in Coupled Yang-Mills Field Dark Energy Models

Wen Zhao*

Department of Physics, Zhejiang University of Technology, Hangzhou, 310014, P. R. China
School of Physics and Astronomy, Cardiff University, Cardiff CF24 3AA, United Kingdom
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We investigate the attractor solution in the coupled Yang-Mills field dark energy models with the general interaction term, and obtain the constraint equations for the interaction if the attractor solution exists. The research also shows that, if the attractor solution exists, the equation-of-state of the dark energy must evolve from $w_y > 0$ to $w_y \leq -1$, which is slightly suggested by the observation. At the same time, the total equation-of-state in the attractor solution is $w_{tot} = -1$, the universe is a de Sitter expansion, and the cosmic big rip is naturally avoided. These features are all independent of the interacting forms.

I. INTRODUCTION

Dark energy problem has been one of the most active fields in the model cosmology, since the discovery of accelerated expansion of universe[1, 2, 3]. In the observational cosmology, the equation-of-state (EOS) of the dark energy $w_{de} \equiv p_{de}/\rho_{de}$ plays a central role, where p_{de} and ρ_{de} are its pressure and energy density, respectively. To accelerate the expansion, the EOS of dark energy must satisfy $w_{de} < -1/3$. The simplest candidate of dark energy is a tiny positive time-independent cosmological constant Λ, whose EOS is -1. However, it is difficult to understand why the cosmological constant is about 120 orders of magnitude smaller that its natural expectation, i.e. the Planck energy scale density. This is the so-called fine-tuning problem. Another puzzle of the dark energy is the first cosmological coincidence problem[4], namely, *why does our universe begin the accelerated expansion recently? why are we living in an epoch in which the dark energy density and the dust matter energy density are comparable?* This problem becomes very serious especially for the cosmological constant as the dark energy candidate. The cosmological constant remains unchanged while the energy densities of dust matter and radiation decrease rapidly with the expansion of our universe. Thus, it is necessary to make some fine-tuning. In order to give a reasonable interpretation to the first cosmological coincidence problem, many dynamical dark energy models have been proposed as alternatives to the cosmological constant, such as quintessence[5], phantom[6], k-essence[7], quintom[8] etc.

Recently, by fitting the SNe Ia data, marginal evidence for $w_{de}(z) < -1$ at redshift $z < 0.2$ has been found. In addition, many best fits of the present values of w_{de} are less than -1 in various data fittings with different parameterizations. The present observational data seem to slightly favor an evolving dark energy with w_{de} crossing -1 from above to below in the near past[9]. In has been found that the EOS of dark energy w_{de} cannot cross the so-called phantom divided $w_{de} = -1$ for quintessence, phantom or k-essence alone[10]. A number of works have discussed the quintom models[8], which is an combination of a quintessence and a phantom. Although many of these models provide the possibility that w_{de} can cross -1, they do not answer another question, namely, *why crossing phantom divided occurs recently?* Since in many existing models whose EOS can cross the phantom divide, w_{de} undulated around -1 randomly, why are we living in an epoch $w_{de} < -1$? It is regarded as the second cosmological coincidence problem[11].

As well known, the most frequently used approach to alleviate the first cosmological coincidence problem is the tracker field dark energy scenario[12]. The dark energy can track the evolution of the background matter in the early stage, and only recently, the dark energy has negative pressure, and becomes dominant . Thus the current condition of the dark energy is nearly independent of the initial condition. If the possible interaction between the dark energy and background matter[13] is considered, the whole system (including the background matter and dark energy) may be eventually attracted into the scaling attractor, a balance achieved, thanks to the interaction. In the scaling attractor, the effective densities of dark energy and background matter decrease in the same manner with the expansion of our universe, and the ratio of dark energy and background matter becomes a constant. So, it is not strange that we are living in an epoch when the densities of dark energy and matter are comparable. In this sense, the first cosmological coincidence problem is alleviated. On the other hand, if the scaling attractor also has the property that its EOS of dark energy is smaller than -1, the second cosmological coincidence problem, if existing, is also alleviated at the same time[11]. However, this is impossible in the interacting quintessence or phantom scenario.

Recently, a number of authors have discussed another class of models, which are based on the conjecture that a vector field can be the origin of the dark energy[14, 15], and have different features to those of scalar field. In the Refs.[16, 17, 18, 19], it is suggested that the Yang-Mills (YM) field can be a kind of candidate for such a vector field. Compared with the scalar field, the YM field is the indispensable cornerstone to particle physics and the

gauge bosons have been observed. There is no room for adjusting the form of effective YM lagrangian as it is predicted by quantum corrections according to field theory. In the previous works[18, 19, 20], we have investigated the 1-loop YM field case and found attractive features: The YM field dark energy models can naturally realize the EOS of $w_y > -1$ and $w_y < -1$, and the current state of the YM dark energy is independent of the choice of the initial condition. The cosmic big rip is also avoided in the models.

In the recent works [21, 22], the 2-loop and 3-loop YM field dark energy are also considered. Although these cases are much more complicated than the 1-loop case, they have not brought new feature for the evolution of the universe. So in this work, we shall only focus on the YM field with 1-loop case.

In this work, the cosmological evolution of the YM dark energy interacting with background prefect fluid is investigated. In fact, gauge fields play a very important role in, and are the indispensable cornerstone to, particle physics. All known fundamental interactions between particles are mediated through gauge bosons. Generally speaking, as a gauge field, the YM field under consideration may have interactions with other species of particles in the universe. However, unlike those well known interaction in QED, QCD, and the electron-weak unification, here at the moment we do not yet have a model for the details of microscopic interactions between the YM field and other particles. In this work, instead of considering some specific assumed interactions between YM field and matter and radiation, which has adopted in [20, 21, 22], we shall consider YM dark energy model with a general interacting term, and investigate the general feature of the attractor solution.

This paper is organized as follows. In Sec.2, we give out the equations of the dynamical system of the interacting YM field dark energy models, and discuss the general features of the interacting models. In Sec.3, we consider three special cases of the interaction terms and the holographic YM dark energy models, and investigate the constraints of these interaction terms. Finally, brief conclusion and discussion are given in Sec.4.

II. DYNAMIC SYSTEM OF INTERACTING YANG-MILLS DARK ENERGY

The effective YM field cosmic model has been discussed in Refs.[16, 17, 18, 19]. The effective lagrangian up to 1-loop order is [24, 25]

$$\mathcal{L}_{eff} = \frac{b}{2} F \ln \left| \frac{F}{e\kappa^2} \right|, \tag{1}$$

where $b = 11N/24\pi^2$ for the generic gauge group $SU(N)$ is the Callan-Symanzik coefficient [26]. $F = -(1/2)F_{\mu\nu}^a F^{a\mu\nu}$ plays the role of the order parameter of the YM field. κ is the renormalization scale with the dimension of squared mass, the only model parameter. The

attractive features of this effective YM lagrangian include the gauge invariance, the Lorentz invariance, the correct trace anomaly, and the asymptotic freedom[24]. With the logarithmic dependence on the field strength, L_{eff} has a form similar to he Coleman-Weinberg scalar effective potential[27], and the Parker-Raval effective gravity lagrangian[28]. The effective YM field was firstly put into the expanding Robertson-Walker (R-W) spacetime to study inflationary expansion[16] and the dark energy[17]. We work in a spatially flat R-W spacetime with a metric

$$ds^2 = a^2(\tau)(d\tau^2 - \delta_{ij}dx^i dx^j), \tag{2}$$

where $\tau = \int (a_0/a)dt$ is the conformal time. For simplicity we study the $SU(2)$ group and consider the electric case with $B^2 \equiv 0$. The energy density and pressure of the YM field are given by

$$\rho_y = \frac{E^2}{2}(\epsilon + b), \quad p_y = \frac{E^2}{2}\left(\frac{\epsilon}{3} - b\right), \tag{3}$$

where the dielectric constant is given by

$$\epsilon = b \ln \left| \frac{F}{\kappa^2} \right|, \tag{4}$$

and the EOS is

$$w_y = \frac{p_y}{\rho_y} = \frac{y-3}{3y+3}, \tag{5}$$

where $y \equiv \epsilon/b = \ln |\frac{F}{\kappa^2}|$. At the critical point with the order parameter $F = \kappa^2$, one has $y = 0$ and $w_y = -1$, the universe is in exact de Sitter expansion [16]. Around this critical point, $F < \kappa^2$ gives $y < 0$ and $w_y < -1$, and $F > \kappa^2$ gives $y > 0$ and $w_y > -1$. So in the YM field model, EOS of $w_y > -1$ and $w_y < -1$ all can be naturally realized. When $y \gg 1$, the YM field has a state of $w_y = 1/3$, becoming a radiation component. The effective YM equations are

$$\partial_\mu(a^4 \epsilon F^{a\mu\nu}) + f^{abc}A_\mu^b(a^4 \epsilon F^{c\mu\nu}) = 0, \tag{6}$$

the $\nu = 0$ component of which is an identity, and the $\nu = 1, 2, 3$ spatial components of which reduce to

$$\partial_\tau(a^2 \epsilon E) = 0. \tag{7}$$

In this work we will generalize the original YM dark energy model to include the interaction between the YM dark energy and dust matter. We assume the YM dark energy and background matter interact through an interaction term Q, according to

$$\dot{\rho}_y + 3H(\rho_y + p_y) = -Q, \tag{8}$$

$$\dot{\rho}_m + 3H\rho_m = Q, \tag{9}$$

which preserves the total energy conservation equation $\dot{\rho}_{tot} + 3H(\rho_{tot} + p_{tot}) = 0$. It is worth noting that the

equation of motion (7) should be changed when $Q \neq 0$. We introduce the following dimensionless variables

$$x \equiv \frac{2\rho_m}{b\kappa^2}, \quad f \equiv \frac{2Q}{b\kappa^2 H}, \tag{10}$$

where f is the function of x and y. By the help of the definition of y, the evolution equations (8) and (9) can be rewritten as a dynamical system, i.e.

$$y' = -\frac{4y}{2+y} - \frac{f(x,y)}{(2+y)e^y}, \tag{11}$$

$$x' = -3x + f(x,y), \tag{12}$$

here, a prime denotes derivative with respect to the so-called e-folding time $N \equiv \ln a$. The fractional energy densities of dark energy and background matter are given by

$$\Omega_y = \frac{(1+y)e^y}{(1+y)e^y + x}, \quad \text{and} \quad \Omega_m = \frac{x}{(1+y)e^y + x}. \tag{13}$$

We can obtain the critical point (y_c, x_c) of the autonomous system by imposing the conditions $y'_c = x'_c = 0$. From the equations (11) and (12), we obtain that the critical state satisfies the following simple relations

$$3x_c = f(x_c, y_c), \tag{14}$$

$$3x_c = -4y_c e^{y_c}, \tag{15}$$

so we can get the critical state (y_c, x_c) by solving these two equations. In order to study the stability of the critical point, we substitude linear perturbations $y \to y_c + \delta y$ and $x \to x_c + \delta x$ about the critical point into dynamical system equations (11) and (12) and linearize them, and obtain two independent evolutive equations, i.e.

$$\begin{pmatrix} \delta y' \\ \delta x' \end{pmatrix} \equiv M \begin{pmatrix} \delta y \\ \delta x \end{pmatrix} = \begin{pmatrix} G_y + R_y & R_x \\ f_y & f_x - 3 \end{pmatrix} \begin{pmatrix} \delta y \\ \delta x \end{pmatrix},$$

where

$$R_y \equiv \partial R/\partial y|_{(y=y_c, x=x_c)}, \tag{16}$$

and the definitions of R_x, f_y, f_x and G_y are similar. The functions G and R are defined by

$$G = G(y) = \frac{4y}{2+y},$$

$$R = R(x,y) = -\frac{f(x,y)}{(2+y)e^y},$$

which are used for the simplification of the notation. The two eigenvalues of the coefficient matrix M determine the stability of the corresponding critical point. The critical point is an attractor solution, which is stable, only if both the these two eigenvalues are negative (stable node), or

real parts of these two eigenvalues are negative and the determinant of the matrix M is negative (stable spiral), which requires that the critical point satisfies the following inequalities

$$G_y + R_y + f_x - 3 < 0, \tag{17}$$

$$[R_x f_y - (f_x - 3)(G_y + R_y)] [(G_y + R_y - f_x + 3)^2 - 4R_x f_y] < 0. \tag{18}$$

or it satisfies

$$G_y + R_y + f_x - 3 < 0, \tag{19}$$

$$(G_y + R_y - f_x + 3)^2 - 4R_x f_y = 0. \tag{20}$$

These generate a constraint of the interaction term Q, which will be shown in the following section.

Here we discuss some general features of the attractor solutions, regardless the special form of the interaction term Q. From the expression (15), we find that $x_c = -\frac{4y_c}{3}e^{y_c}$. Substitute this into the formula (13), one obtains

$$\Omega_y = \frac{(y_c + 1)e^{y_c}}{(y_c + 1)e^{y_c} + x_c} = \frac{3 + 3y_c}{3 - y_c}. \tag{21}$$

Since $0 \le \Omega_y \le 1$, this formula follows a constraint of the critical point

$$-1 \le y_c \le 0. \tag{22}$$

From the formulae (5) and (21), we obtain

$$\Omega_y w_y = -1. \tag{23}$$

This relation is kept for all attractor solutions, independent of the special form of the interaction. Since the value of Ω_y is not larger than one in the attractor solution, we obtain that

$$w_y \le -1, \tag{24}$$

the EOS of the YM dark energy must be not larger than -1, phantom-like or Λ-like. Since in the early universe, the value of the order parameter of the YM field F is much larger than that of κ^2, i.e. $y \gg 1$, the YM field is a kind of radiation component[19]. However, in the late attractor solution, the dark energy is phantom-like or Λ-like. So the phantom divide must be crossed in the former case, which is different from the interacting quintessence, phantom or k-essence models.

In order to the investigate the finial fate of the universe, we should investigate the total EOS in the universe, which is defined by

$$w_{tot} \equiv \frac{p_{tot}}{\rho_{tot}} = \frac{p_y + p_m}{\rho_y + \rho_m} = \Omega_y w_y, \tag{25}$$

where $p_m = 0$ is used. From the relation (23), we obtain that, in the attractor solution,

$$w_{tot} = -1. \tag{26}$$

This result is also independent of the special form of the interaction. So the universe is an exact de Sitter expansion, and the cosmic big rip is naturally avoided, although the YM field dark energy is phantom-like.

III. SEVERAL INTERACTION MODELS

In the previous section, we find the critical point of the dynamical system of interacting YM dark energy models satisfies not only the equations in (14) and (15), but also the constraint of (22). It is obvious that the expression of (14) depends on the special form of interacting term. If the critical point is an attractor, it also satisfies the constraint in (17) and (18), or in (19) and (20). These relations can give some constraints of the interaction term. In this section, we consider several cases with different interaction forms between the YM dark energy and background matter, which are taken as the most familiar interaction terms extensively considered in the literature[13].

Case a: $Q \propto H\rho_y$, which is equivalent to the form $f(x, y) = \alpha(y+1)e^y$, where α is a dimensionless constant. From the equations (14) and (15), we obtain the critical point

$$y_c = -\frac{\alpha}{4 + \alpha}, \quad x_c = -\frac{4y_c}{3}e^{y_c}. \tag{27}$$

The constraint in (22) requires that

$$\alpha \geq 0, \tag{28}$$

and the attractor conditions in (17)-(20) require that

$$\alpha > -8. \tag{29}$$

So we obtain the constraint of the interaction from, if the attractor solution exists, the parameter α satisfies

$$\alpha \geq 0, \tag{30}$$

and the EOS and the fractional energy density of the YM field in the attractor solution are

$$w_y = -\frac{1}{3}(\alpha + 3), \quad \Omega_y = \frac{3}{\alpha + 3}, \tag{31}$$

respectively. It is obvious that $w_y \leq -1$.

Case b: $Q \propto H(\rho_y + \rho_m)$, which is equivalent to the form $f(x, y) = \beta[(y+1)e^y + x]$, where β is a dimensionless constant. From the equations (14) and (15), we obtain the critical point

$$y_c = \frac{3\beta}{\beta - 12}, \quad x_c = -\frac{4y_c}{3}e^{y_c}. \tag{32}$$

The constraint in (22) requires that

$$0 \leq \beta \leq 3, \tag{33}$$

and the attractor conditions in (17)-(20) require that

$$\beta < \frac{120}{31}. \tag{34}$$

So the parameter α satisfies

$$0 \leq \beta \leq 3, \tag{35}$$

if the critical state is an attractor solution. The EOS and the fractional energy density of the YM field in the attractor are

$$w_y = \frac{3}{\beta - 3}, \quad \Omega_y = \frac{3 - \beta}{3}, \tag{36}$$

respectively, which follows that $w_y \leq -1$, the YM field dark energy is phantom-like or Λ-like.

Case c: $Q \propto H\rho_m$, which is equivalent to the form $f(x, y) = \gamma x$, where γ is a dimensionless constant. From the equations (14) and (15), we easily nd that they have no solution except that the value of γ is exactly zero, i.e. the case with no interaction.

Case d: Recently, a number of authors have discussed the holographic dark energy, where the holographic principle has been put forward to explain the dark energy. According to the holographic principle, the number of degrees of freedom of a physical system scales with the area of its boundary. In the context, Cohen et al[29] suggested that in quantum field theory a short distant cutoff is related to a long distant cutoff due to the limit set by formation of a black hole, which results in an upper bound on zero-point energy density. In line with this suggest, Hsu and Li[30, 31] argued that this energy density could be views as the holographic dark energy satisfying

$$\rho_{de} = 3d^2 M_P^2 L^{-2}, \tag{37}$$

where $d \geq 0$ is a numerical constant, and $M_P \equiv 1/\sqrt{8\pi G}$ is the reduced Planck mass. L is the size of the current universe. Li[31] proposed that the IR cut-off L should be taken as the size of the future event horizon

$$L = R_{eh}(a) = a \int_t^\infty \frac{d\tilde{t}}{a(\tilde{t})} = a \int_a^\infty \frac{d\tilde{a}}{H\tilde{a}^2}. \tag{38}$$

In this letter, we consider the holographic YM field dark energy. From the relation (37), one obtains that

$$\dot{\rho}_y = \dot{\rho}_{de} = 6M_p^2 \Omega_y H^3 \left(\frac{\sqrt{\Omega_y}}{d} - 1 \right), \tag{39}$$

which follows that the interaction form is

$$Q = -2\rho_y H \left(\frac{\sqrt{\Omega_y}}{d} - 1 \right) - 3H\rho_y(1 + w_y), \tag{40}$$

where the expression (8) is used. This formula is equivalent to the form

$$f(x, y) = \left[-\frac{4y}{y+1} - 2 \left(\frac{\sqrt{\frac{3+3y}{3-y}}}{d} - 1 \right) \right] (y+1)e^y. \tag{41}$$

From the equations (14) and (15), we obtain the critical point

$$y_c = -\frac{3(d^2 - 1)}{3 + d^2}, \quad x_c = -\frac{4y_c}{3}e^{y_c}. \tag{42}$$

The attractor conditions in (17)-(20) require that

$$d < 0, \qquad (43)$$

which is conflicting with the previous assumption $d \geq 0$. So we get the conclusion: the holographic YM dark energy model has no attractor solution.

IV. CONCLUSION AND DISCUSSION

In summary, the cosmological evolution of the Yang-Mill field dark energy interacting with background matter is investigated in this letter. We find the features of the interacting YM dark energy models:

a. The interaction term between the YM dark energy model and the matter has a fairly tight constraint, if we require that the attractor solution of the model exists.

b. If the attractor solution exists, the EOS of the YM field must evolve from $w_y > 0$ to $w_y < -1$ or $w_y = -1$.

c. The holographic YM dark energy model has no attractor solution, which is different from other holographic models[32].

d. In the attractor solution, the total EOS is $w_{tot} = -1$, which is independent of the interacting forms. So the universe is in a de Sitter expansion, and the cosmic big rip does not exist in the models.

In the interacting YM dark energy models, we should notice the "fine-tuning" problem, which is reflected by the value of κ, the energy scale of the Yang-Mills field dark energy models. In the interacting models, the total energy density in the universe is

$$\rho_{tot} = \frac{\rho_m}{\Omega_m} = \frac{b\kappa^2}{2} \left[(1+y) e^y + x \right]. \qquad (44)$$

In the attractor solution, we can obtain

$$\rho_{tot} = \frac{b\kappa^2}{2} \left(1 - \frac{1}{3} y_c \right) e^{y_c}. \qquad (45)$$

where the express (15) is used. The value of ρ_{tot} should be not larger than which of the present total energy density in the universe[23], i.e.

$$\rho_{tot} \leq 8.099 h^2 \times 10^{-11} eV^4, \qquad (46)$$

which leads to

$$\kappa \leq 4.18 h \times 10^{-5} eV^2 \left(1 - \frac{1}{3} y_c \right)^{-1/2} e^{-y_c/2}. \qquad (47)$$

For a fixed interacting models, where y_c can be obtained, one can exactly calculate the value of the κ, which keeps the current energy density of YM dark energy being current observed value. From (47), we find that this energy scale κ is, as well as the case with free Yang-Mills field models, very low compared to the typical energy scales in particle physics.

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